The extremely-long-runout Komansu rock avalanche in the Trans Alai Range, Pamir Mountains, Southern Kyrgyzstan.

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Abstract

Massive rock avalanches form some of the largest landslide deposits on Earth and are major geohazards in high-relief mountains. This work reinterprets a previously-reported glacial deposit in the Alai Valley of Kyrgyzstan as the result of an extremely long-runout, probably coseismic, rock avalanche from the Komansu River catchment. Total runout of the rock avalanche is ~28 km, making it one of the longest-runout subaerial non-volcanic rock avalanches thus far identified on Earth. This runout length appears to require a rock volume of ~20 km^3; however the likely source zone in the Trans Alai range likely contained just ~4 km^3 of rock and presently the deposit has a volume of only 3-5 km^3; a pure rock avalanche volume of > 10 km^3 is therefore impossible, so the event was much more mobile than most non-volcanic rock avalanches. Explaining this exceptional mobility is crucial for present day hazard analysis. There is unequivocal sedimentary evidence for intense basal fragmentation, and the deposit in the Alai valley has prominent hummocks; these indicate a rock avalanche rather than a rock-ice avalanche origin. The event occurred 5000-11000 yr B.P., after the region's glaciers had begun retreating, implying that supraglacial runout was limited. Current volume – runout relationships suggest a maximum runout of ~10 km for a 4 km^3 rock avalanche. Volcanic debris avalanches, however, are more mobile than non-volcanic rock avalanches due to their much higher source water content; a rock avalanche containing a similarly high water content would require a volume of about 8 km^3 to explain the extreme runout of the Komansu event. Rock and debris avalanches can entrain large amounts of material during runout, with some doubling their initial volume. The best current explanation of the Komansu rock avalanche thus involves an

initial failure of ~4 km^3 of rock debris, with high water content probably deriving from large glaciers on the edifice, that subsequently entrained ~4 km^3 of valley material together with further glacial ice, resulting in a total runout of 28 km. It is as yet unclear whether glacial retreat has rendered a present-day repetition of such an event impossible.

Keywords

Rock avalanche; long-runout; basal fragmentation; extreme mobility; water content; entrainment

Introduction

Large (>10^6 m^3) rock avalanches with unusually long run-out distances (up to tens of kilometres) occur infrequently in mountain ranges and from volcanic edifices. Rock avalanche deposits have been identified at numerous locations on Earth as well as on Mars and the Moon (e.g. Lucchitta, 1978; Quantin et al., 2004; Lucas and Mangeney, 2007). Their deposits often bear a striking morphometric resemblance to glacial deposits, sometimes resulting in misinterpretation: for example, re-examination of deposits in the Karakoram Himalayas by Hewitt (1999) resulted in 15 previously-reported glacial deposits being re-interpreted as rock avalanche deposits. Similar re-interpretations have also occurred elsewhere (e.g. McColl and Davies, 2010; Barth, 2013). Incorrectly identifying rock avalanche deposits as glacial deposits can result in underestimated geohazards risk (McColl and Davies, 2010), whilst also contaminating regional paleoclimate reconstructions vital for understanding global climate dynamics (Reznichenko et al, 2012).

Large rock avalanches are typically characterised by long runouts resulting in unusually small apparent coefficients of friction (=H/L; where H is the total fall height and L is the total travel distance; Hsü, 1975). Many explanations for this apparent reduction of friction have been proposed including air cushioning (Shreve, 1966), acoustic fluidisation (Melosh, 1979), mechanical fluidisation (Davies, 1982), and lubrication from molten basal layers (Erismann, 1979). However, currently none of these explanations are generally accepted within the scientific community (Davies and McSaveney, 2012). Rock avalanches can be triggered by a number of different factors including strong ground motions during earthquakes, volcanic eruptions, heavy or long-duration rainfall, rapid snow melt, or a combination of these. In addition, some lack any definitive trigger (e.g. Sigurdsson and Williams, 1991; McSaveney, 2002; Hauser, 2002). Identifying the cause of a prehistoric event is therefore difficult; however, analysis of the local and regional environment as well as estimates of the timing of the event can provide some insights. Additionally, analysis of the deposit morphology and of the internal structure, if exposed, can offer understanding of the emplacement dynamics.

The intramontane Alai Valley in the Northern Pamir Mountains of Kyrgyzstan (Fig. 1) has numerous large-scale deposits previously interpreted as glacial moraines (e.g. Nikonov et al., 1983; Arrowsmith and Strecker, 1999; Strecker et al., 2003). However, recent analysis by Reznichenko et al. (2013) of a deposit on the true right of the Komansu River determined that it is of rock avalanche origin. This deposit (Fig. 2) was first identified as a rock avalanche by Kurdiukov (1964), however was later reinterpreted by Nikonov et al. (1983) as a moraine, and recently Strom (2014) suggested it was the result of a mixed rock-ice avalanche. The deposit extends north from the Trans Alai ranges of the Pamir Mountains for 28 km to the foothills of the Tien Shan Mountains (Fig. 2), making it one of the longest-runout subaerial rock avalanche deposits identified on Earth. The deposit is exposed at the surface only for the distal half of its runout, with no evidence identified in the proximal section of the runout (Fig. 2). Present-day surface expression of the deposit covers an area of 64 km^2 however the original deposit likely covered an area of the order of 100-150 km^2 immediately after it was emplaced (Fig. 2), the rest having been eroded or buried subsequently.

This study aims to clarify the nature of the Komansu rock avalanche event including the failure mechanism and the dynamic processes involved during runout, based on field surveys and the interpretation of aerial and satellite images. We also discuss the implications for hazard analysis of such events.

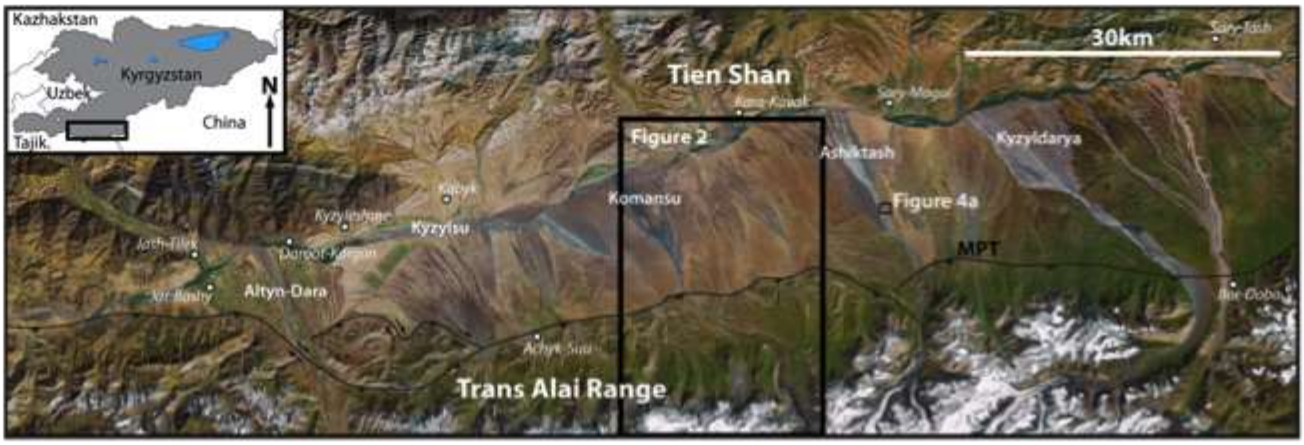

Fig 1 Satellite image of the Alai Valley showing the major villages, rivers, mountain ranges within the region. MPT – Main Pamir Thrust. Boxes indicate areas shown in Figures 2 & 4a

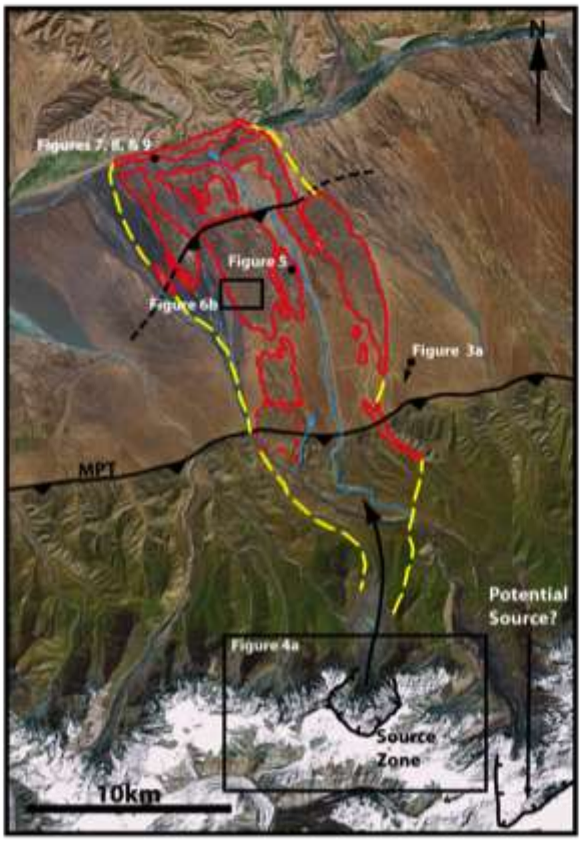

Fig 2 Komansu River catchment showing the exposed Komansu rock avalanche deposit, with probable source headscarp and runout path. Black lines show fault scarps; MPT – Main Pamir Thrust; thick black arrow shows likely runout path; solid red lines show surficial exposure of the deposit; dashed red line shows possible rock avalanche deposit; yellow dashed lines show inferred extent of the deposit immediately after emplacement; blue lines show the inferred position of the Komansu River immediately after emplacement (see text); black circles show location of figures. Boxes indicates area shown in corresponding figures.

<u>Regional Setting</u>

<u>Tectonics</u>

The Komansu deposit lies in the centre of the Alai Valley in southern Kyrgyzstan, between the Pamir and Tien Shan Mountains (Fig. 1). The Alai Valley separates the Trans Alai (also known as Zaalai) range of the Northern Pamir from the Tien Shan and was formerly part of a contiguous Cenozoic sedimentary basin, connecting the Tajik depression in the west with the Tarim basin in the east (Strecker et al, 2003). The Trans Alai range, which makes up the southern boundary of the Alai Valley, formed as a result of Eurasian crust being over-thrust by the Pamir block during the late Oligocene-early Miocene (Burtman and Molnar, 1993; Coutand et al., 2002) due to the Indo-Eurasian collision to the south. As a result, the Trans Alai range reaches elevations over 7000 m with

3000-3500 m of relief. The range is composed mainly of amalgamated and heavily deformed Paleozoic and Mesozoic terrains while the Alai Valley consists primarily of large Quaternary alluvial fans, moraines, and landslide deposits (Arrowsmith and Strecker, 1999). North of the valley, the Tien Shan rises to over 5000 m with 2000-2500 m relief and is characterised by Devonian limestones and Carboniferous metasediments overlain by Jurrasic conglomerates and sandstones (Strecker et al., 2003).

Present shortening between the Trans Alai range and Tien Shan estimated from repeated GPS measurements is 15-30 mm yr^{-1} (Burtman and Molnar, 1993; Arrowsmith and Strecker, 1999) which accommodates between $^{1}/_{3}$ and $^{2}/_{3}$ of the relative Indo-Eurasian Plate deformation at this location. Most of this shortening is thought to occur along the range-bounding Main Pamir Thrust (MPT; Figs. 1 & 2). Arrowsmith and Strecker (1999) estimated that the dip-slip rate along this fault must be at least 6 mm yr^{-1} based on geologic observations while Krumbiegel et al. (2011) estimate a rate of 13 mm yr^{-1} based on geodetic observations. These rapid rates of convergence are supported by the high seismicity along the MPT with several recent major earthquakes along the fault including M7.4 in 1949; M7.3 in 1974 (Zubovich et al, 2009); M6.5 in 1978 (Fan et al, 1994) and M6.7 in 2008 (Zubovich et al, 2009; Krumbiegel et al, 2011).

Quaternary History

Due to the remote location and high elevation relatively limited research has been undertaken in the area, resulting in an incomplete Quaternary history. Nevertheless, recent work by Shatravin (2000) used oxide/protoxide ratios of alluvial and proluvial deposits and proposed that the last maximum glacial extent occurred 30,000 years before present (yr B.P.) with a smaller Holocene re-advance around 8,000 yr B.P. According to Arrowsmith and Strecker (1999) and Shatravin (2000) the period between the Pleistocene glacial maximum and the Holocene re-advance is represented in the geologic record by numerous large landslide deposits. These deposits consist mainly of Neogene sandstones and argillites sourced from the Trans Alai range and typically have a hummocky topography and corresponding arcuate detachment scars (Arrowsmith and Strecker, 1999). Arrowsmith and Strecker (1999) suggested that the largest of these had a runout of 5-6 km from the mountain front.

The Komansu source and deposit

Our re-interpretation of the Komansu deposit from a moraine to a rock avalanche event is the result of detailed ground investigations including analysis of the geomorphology as well as the sedimentology of the deposit (Reznichenko et al, 2013).

Source

The location and extent of the Komansu deposit suggest that the rock avalanche has a source zone in the Trans Alai range (Fig. 2). This range is >7000 m high, and contains numerous glaciers. As a result we could not definitively identify the source zone. Nevertheless, far-field observation of the mountain range combined with satellite images and field mapping allowed us to identify a probable source zone (Figs. 2 & 3). This shows the arcuate bowl shape typical of a large rock avalanche source (Turnbull & Davies, 2006) and is suitably located and orientated to generate the current Komansu rock avalanche deposit (Fig. 2). We have attempted to reconstruct the pre-failure paleo-topography of this source zone in order to estimate the likely initial volume of debris involved in the collapse (Fig. 4). These estimates suggest that the initial landslide body contained a volume of up to 4 km^3 of initially intact rock and, including a 25% bulking factor due to fragmentation, gives a maximum total failure volume of ~4-5 km^3. Smaller volumes are of course possible corresponding to reconstructions that put the paleo-ridgeline at a lower elevation

Other large scars are present within the area, including one 8 km east of the suggested source zone (Fig. 2). However, this is much less suitably orientated to generate a deposit in the same location as the Komansu deposit, and, although larger, would mean an even longer runout.

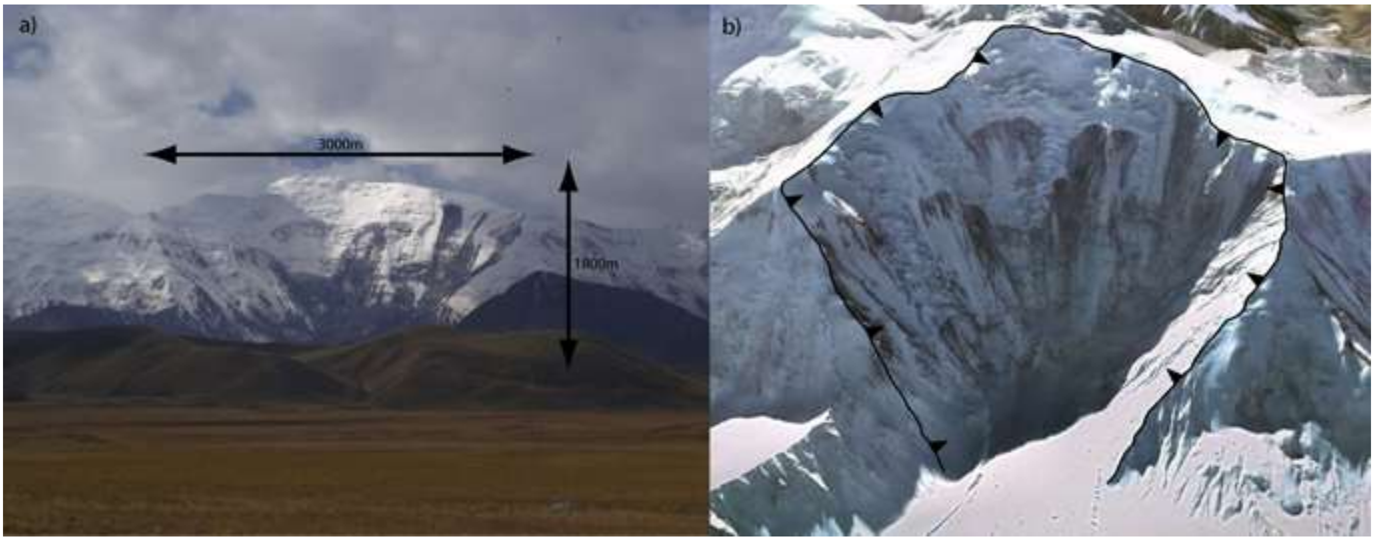

Fig 3 a) Field photograph looking SW at the probable source zone for the Komansu rock avalanche deposit with dimensions (see Fig 2 for location); b) Google Earth image (looking SE) of the probable source zone showing the detachment scar. Another large scar 8 km farther east is less well situated with respect to the deposit so was discounted.

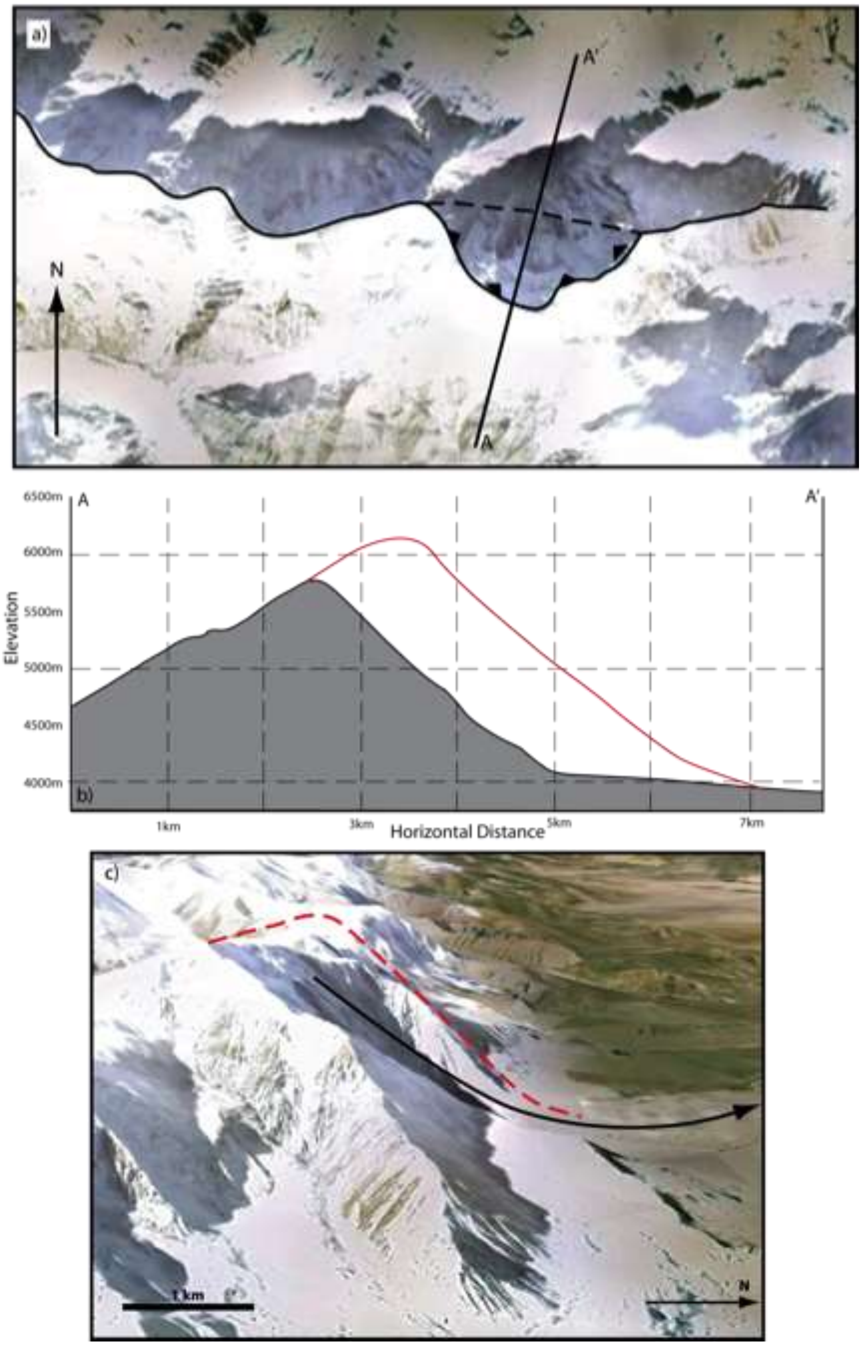

Fig 4 Reconstruction of source area pre-collapse topography. a) Interpreted position of original ridgeline; solid line shows present day ridgeline; dashed line shows inferred paleo-ridgeline; triangles denote rock avalanche scar; profile A-A' shown in b). b) Present day topography (shaded) derived from Google Earth with inferred paleo-topography (red) denoting the landslide body. c) Google Earth view of the source zone looking east showing the inferred paleo-topography

Deposit dimensions

As shown in Fig. 2, the deposit extends across the full width of the Alai valley, and extends a short distance up the southern slopes of the Tien Shan. It is exposed at the surface only for the distal half of its runout, with no evidence identified in the proximal section of the runout (Fig. 2). The present-day surface expression of the deposit is not continuous, but is divided into a number of discrete areas by fluvially-altered terrain. We assume that the original deposit was contiguous, and has been partially reworked since emplacement by fluvial activity.

Only very limited deposits corresponding to that in the Alai valley have been found between the source area and the Alai valley (the valley reach). We assume that the event deposited material here which has subsequently been eroded or buried by glaciofluvial processes. The present area of rock-avalanche deposit is 64 km^2, however the original deposit likely covered an area of 100-150 km^2 immediately after it was emplaced (Fig. 2), the rest having been eroded or buried subsequently.

Deposit volume

The volume of the event can be estimated from its deposit area, if a deposit depth is known or can be estimated. Unfortunately the basal contact of the deposit is only visible at the distal end, where the depth is ~ 10 m. This is expected to be the minimum, since all large-volume mass movements are thinnest distally. The prominent hummocks are ~ 20 m and up to 40 m high over most of the remaining deposit, suggesting a deposit depth of several tens of metres, so the inferred surface area of 100-150 km^2 would give a total volume of about 3-5 km^3. The depth of deposit in the valley reach would be likely to be significantly greater than on the flat Alai valley, so this estimate seems likely to be rather low and 5-10 km^3 may be more realistic for a total volume. However we note that this is substantially larger than the volume contained in the source zone, suggesting the event may have had substantial entrainment.

A further volume estimate can be derived from regression of runout length against volume for other rock avalanches. Without accurate, reliable volume data for the Komansu event, regression analysis allows us to estimate the volume necessary to explain the runout length. One of the simplest regressions was that of Davies (1982) who found that for rock avalanches in non-glaciated environments

$$L \sim 10(V)^{1/3} \tag{1}$$

where L is the deposit length and V is the deposit volume. If L = 26 km (total runout less headscarp length), then $V \sim 2.6^3 = 18\ km^3$. This is significantly greater than either the deposit volume or the headscarp volume, indicating that the Komansu event was significantly more mobile than most other large rock avalanches.

Surface Morphology

The Komansu deposit is clearly distinguishable from the surrounding alluvial deposits by its pronounced hummocky terrain. These hummocks are small conical hills, averaging around 20 m in height but up to 40 m in places, and averaging 50-60 m in diameter (Fig. 5). Arrowsmith and Strecker (1999) described hummocky topography as being present in both glacial and landslide deposits within the Alai Valley, and such hummocks have been identified in other large rock avalanche deposits including those at Socompa in Chile (Wadge et al, 1995) and Fernpass in the European Alps (Prager et al., 2006) amongst others. Hummocky terrain in the rock avalanche deposit from Round Top in New Zealand is thought to have resulted from runout over outwash surface (Dufresne et al., 2010) which would also have occurred during the Komansu event. Nevertheless, hummocks are not definitive evidence of rock avalanches because they can also be characteristic of moraines, and thus Nikonov et al. (1983) and Arrowsmith and Strecker (1999) interpreted the Komansu deposit as of glacial origin. However, in the Alai Valley glacial hummocks are typically larger than those of the Komansu deposit and contain kettle-hole deposits formed during glacial melt-out, none of which were identified in the Komansu deposit (Reznichenko et al, 2013). Figure 6 shows a comparison of the larger hummocks of the Achiktash catchment glacial deposit ~20 km east of the study area and the smaller, more uniform hummocks of the Komansu rock avalanche deposit.

Fig 5 Hummocky terrain of the Komansu deposit with the Trans Alai range in the background. View looking SW (see Fig. 2 for location).

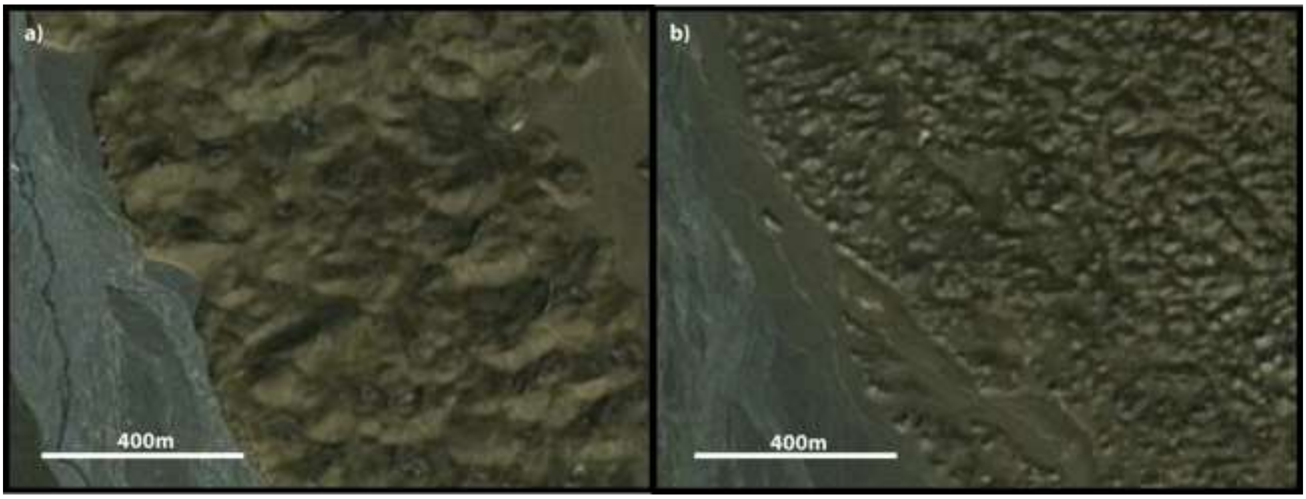

Fig 6 Comparison of hummocks from the a) Achiktash moraine deposit and b) Komansu rock avalanche deposit. Images from Google Earth.

Sedimentology

Clast counts were undertaken at several locations on the Komansu rock avalanche deposit to characterise lithology, clast size, and roundness in an attempt to infer its likely origin. The deposit is matrix-supported (although appears clast-supported in places) and dominated by angular to very angular and occasionally sub-rounded argillite and quartzite clasts of fine pebble to boulder size, in a matrix of very much finer material. These sediment characteristics correspond closely to reported descriptions of rock avalanche deposits which comprise a fragmented mass of angular to very angular clasts of the source lithology. Hewitt (1999) used this description to identify 15 rock avalanche deposits in the Karakorum Himalayas previously identified as moraines. The mainly argillite composition of the Komansu deposit agrees with the observation of Arrowsmith and Strecker (1999) of the lithologic composition of several other landslide deposits in the region whose sources are also in the Trans Alai range.

Reznichenko et al. (2012) developed a method to identify sediment of rock avalanche origin by the presence of characteristic micron-scale agglomerates of widely-graded, largely subangular sub-micron clasts of parent material lithologies, as observed under a Scanning Electron Microscope (SEM). These agglomerates are the result of intense comminution of intact rock, and rebonding of the smallest fragments, under rapid, high-stress conditions during rock avalanche runout, and are absent from sediments produced in lower stress and strain-rate glacial processes. Samples from the Komansu deposit were shown by Reznichenko et al. (2013) to contain micron scale agglomerates and hence they deduced a rock avalanche origin of the hummocky deposit, confirming our sedimentologic and morphologic deduction.

Basal Contact

The Kyzylsu River, which flows east-west through the Alai Valley (Fig. 2), has eroded through the distal part of the deposit and exposed a long basal contact (Fig. 7). This sharp unconformity separates the rock avalanche body from the alluvial terrace deposits beneath. At the eastern extent of the outcrop the contact curves upwards before flattening out, thinning the rock avalanche deposit (Fig. 8a). Planar horizontal bedding in the underlying alluvium is clearly truncated at this contact (Fig. 8b) and we interpret this alluvium as an ancient Kyzylsu River terrace which was over-ridden and partly preserved by the rock avalanche. The lack of erosion and preservation of underlying alluvial stratigraphy is further evidence of a rock avalanche origin rather than a glacial origin.

In the distal exposure of the Komansu deposit we found a concentrated basal shear layer (Fig. 9), where clasts had been ground excessively fine by interparticle stresses due to the shearing motion during runout (Davies & McSaveney, 2009).

Fig 7 Basal contact between Komansu rock avalanche deposit and alluvial deposits. Maximum cliff height is ~15m. View looking north (see Fig 2 for location).

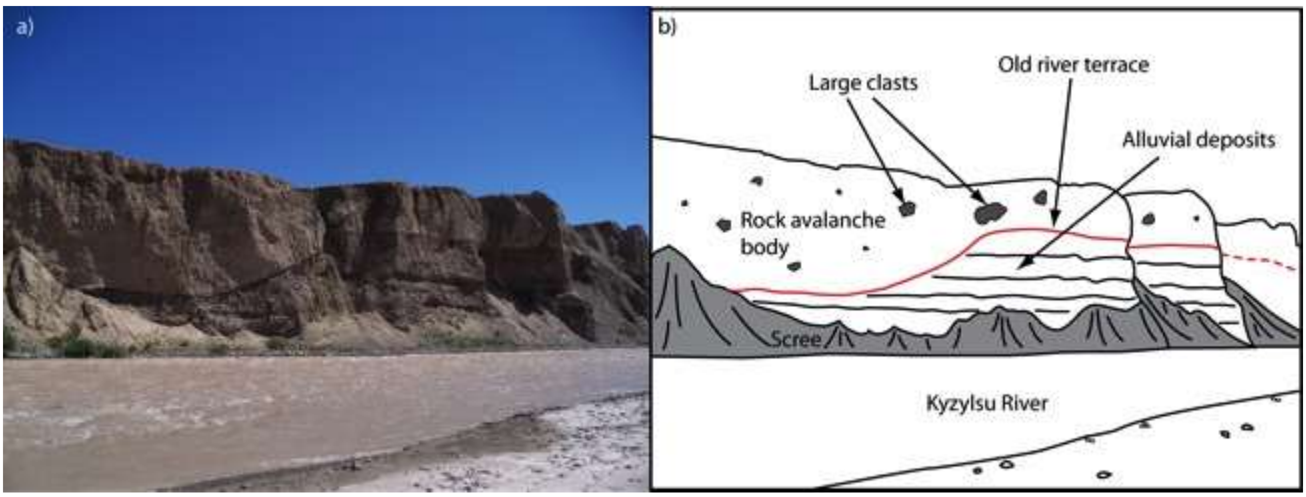

Fig 8 a) View of rock avalanche basal contact with underlying alluvial deposits, looking NE (see Fig 2 for location); b) Interpretation. Maximum cliff height is ~15m. Red line shows position of basal contact.

Overlying Units

Overlying the rock avalanche deposit is a variable cover of fine-grained loess with thicknesses ranging from tens of centimetres to several metres. However, most of the loess and characteristic hummocks in the central section of the deposit have been eroded away, corresponding with the location of an abandoned river course (Fig. 2). Here the overlying deposits consist of alluvial sediments similar to those beneath the rock avalanche deposit in Figs. 8 and 9. It is inferred that after the rock avalanche deposit was emplaced, the Komansu River flowed through the centre of the deposit, eroding it and depositing alluvial sediments. Subsequently the river changed course to its present position on the western flank of the deposit where it incised into its present canyon during uplift along the MPT.

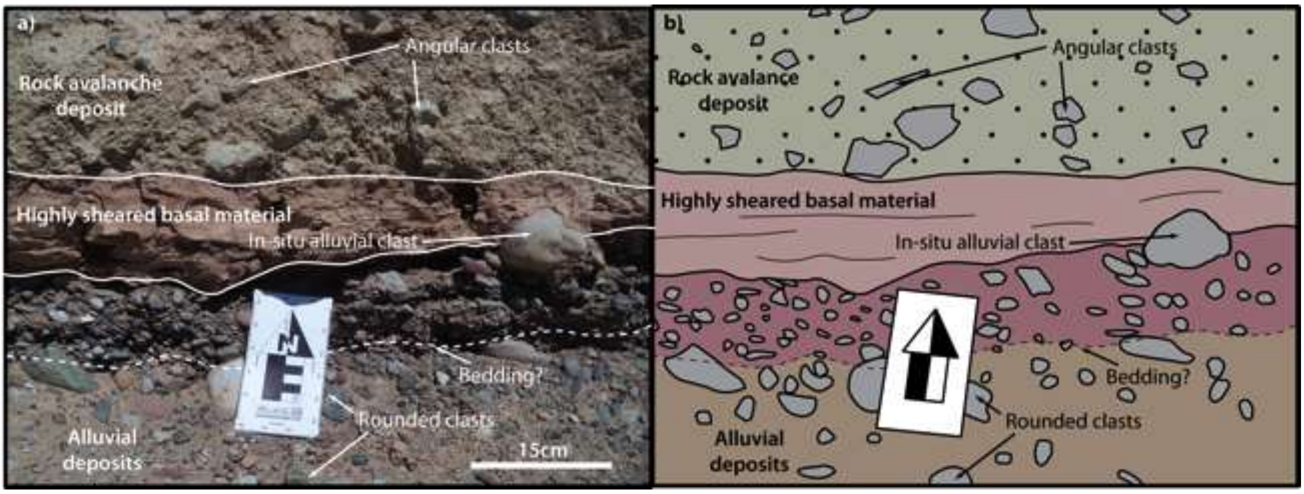

Fig 9 Interpreted photo (a) and sketch (b) of basal contact between rock avalanche deposit and alluvial deposits. Note the highly sheared material at the base of the rock avalanche deposit which has flowed over the alluvial deposits without moving the large clast at the right of the image. This suggests relatively low basal shear stress as required by the long runout.

The emplacement event

Based on the descriptions above we now consider the characteristics of the emplacement event.

Timing

Arrowsmith and Strecker (1999) suggested that the majority of landslide deposits they identified in the region date to the Late Pleistocene and Early Holocene. We identify circumstantial evidence which suggests that the Komansu rock avalanche also corresponds to the Holocene.

The rock avalanche deposit itself has two continuous thrust fault scarps of the MPT running through it (Fig. 2) with 30 m high surface displacements. These scarps represent multiple surface ruptures along the MPT through the deposit since it was emplaced. On major faults such as the MPT, recurrence intervals between major earthquakes are *at least* several hundred years (e.g. Lienkaemper et al. 2012) which suggests a deposit age of at least several thousand years is required. Using the estimated slip rates along the MPT suggests an age of 2,300-5,000 years. However, field mapping during this study identified an additional trace of the MPT with tens of metres of offset at the surface, 10 km north of the main MPT trace (Fig. 2). Two traces of the fault requires the 2.3-5.0 ka ages to be doubled to ~5 to 11 ka, if both traces of the fault accommodate regional deformation. Alternatively, however, the deposit could have overridden and preserved these fault scarps similar to the preserved Kyzylsu River terrace at the distal end (Fig. 8). This would suggest the deposit was very much younger than the 5-11 ka suggested however, the fragmented nature of the present-day surficial exposure, and the absence of debris in the reach valleys (Fig. 2), suggest an age of several thousand years is most likely.

The lack of surficial exposure of the deposit in its proximal confined-valley section has two possible explanations relevant to the timing of the event. Either the rock avalanche travelled across a glacier and did not deposit any material, or the deposit was subsequently eroded or buried by glaciofluvial processes. For the rock avalanche to have travelled the first ~15 km of its runout along glacial ice requires it to have occurred at a time when the glaciers were substantially more advanced than at present. Despite the suggested age for the deposit being considerably after the last glacial maximum, the upper age estimate corresponds to a time when the regions glaciers were likely to still be more advanced than today. In any case, however, it seems extremely unlikely that a rock avalanche would travel for such a large distance – even over ice - without depositing any material. While other rock avalanches have been known not to generate proximal deposits (e.g. Seit in central Kyrgyzstan; Strom, 2006) the area without deposit is in these cases is relatively small and far less than the 15 km seen in the Komansu event; further, most rock avalanches that travel over glaciers completely cover the proximal area with debris. This strongly (but not conclusively) suggests that deposition occurred in the upper valley reaches but was subsequently eroded or buried by glaciofluvial processes. Analysis of the deposit age alone is therefore insufficient to determine whether or not runout over glacial ice occurred; however, inspection of the excessive runout length may provide some insight.

Runout Velocity

The deposit is present on both banks of the Kyzylsu River (Fig. 2) and clearly moved uphill as it reached the opposing slope of the Tien Shan. The distal end of the deposit is up to 100 m higher than its lowest point on the true left bank of the Kyzylsu River. If the kinetic energy of the rock avalanche was converted completely to gravitational potential energy as it ran uphill, the rock avalanche must have been travelling at least 45 m s^{-1} (~160 km hr^{-1}) when it reached the Tien Shan. This is a *minimum* estimate of its velocity assuming that all kinetic energy was transferred to potential energy; in reality much of the kinetic energy will be lost to friction, heat, sound etc. so the velocity would have been greater. A rock avalanche travelling at this velocity, unimpeded, would likely continue to runout for several additional kilometres.

Initiation

Establishing the trigger for a prehistoric event such as the Komansu rock avalanche is difficult and requires a number of assumptions. Nevertheless, a most likely cause can be arrived at by a process of elimination. This region is especially arid and has likely been so for the majority of the Quaternary period (e.g. Abramowski et al., 2006), making heavy or long-duration precipitation unlikely. Furthermore, rainstorms rarely result in large, deep-seated rock slope failures such as that required for the Komansu event, thus we do not consider this a likely cause. Similarly, rapid snow melt and permafrost degradation are unlikely to result in deep-seated failures. The most likely trigger is therefore strong ground motion during a large local earthquake. The MPT is the main structure that has accommodated tectonic uplift in this region throughout the last several million years; importantly, there are MPT fault scarps up to ~30 m high running through the deposit that represent multiple ruptures along the MPT in the area since the rock avalanche was deposited (Arrowsmith and Stecker, 1999). Furthermore, the MPT is known to be capable of generating large (>M7.0) earthquakes and is sufficiently close to the Trans Alai ranges to generate high intensity shaking in the source region, with substantial topographic amplification in the upper parts of the range (Buech et al., 2010). Historically, large earthquakes are known to have caused large-volume rock avalanches with excessive runouts. The Bogd Fault, Saidmarreh, Green Lake, Tsergo Ri, Falling Mountain and Lluta events are all inferred to have seismic triggers associated with nearby major fault systems (Phillip and Ritz, 1999; Roberts and Evans, 2013; Hancox and Perrin, 1994; Weidinger et al., 1996; Davies and McSaveney, 2002; Strasser and Schulnegger, 2005). It therefore seems likely that the Komansu rock avalanche was initiated by a large (>M7.0) earthquake occurring on the MPT in the central Alai Valley.

Emplacement mechanism

The unusually high mobility of the Komansu deposit is its best-contrained characteristic, and is also a serious concern from a hazard perspective; if a rock avalanche can run out twice as far as others of its type, there is a need to understand why. The long runout can be explained in a number of different ways: a) the original volume was very much larger than the remaining deposits; b) the incorporation of large volumes of ice into the rock debris; or c) the runout took place over glacier ice. We now consider each of these in turn.

1. *Large-volume rock avalanche*

The identification by Reznichenko et al. (2013) of rock-avalanche-sourced fines in the distal basal layer of the deposit is indicative of a rock avalanche. Such fines are not produced by the lower stress and strain rates of glacial processes, and have not been identified in historic rock-ice avalanche deposits; the latter, being saturated, would be unlikely to show the basal shear seen in the Komansu deposit.

To date only two reported terrestrial subaerial non-volcanic rock avalanches have runouts greater than 28 km (Table 1). If the Komansu event follows the deposit length–volume relationships for rock avalanches identified by many authors since Scheidegger (1973) (e.g. Eq. 1), then the volume must have been ~20 km^3. This would make the Komansu event one of the largest identified terrestrial rock avalanches (Table 1). As noted above, the dimensions of the source area show that the initial volume is substantially less than the ~20 km^3 required for a rock avalanche with 28 km runout. An alternative mechanism is therefore likely to have been involved.

Rock Avalanche	**Volume (km^3)**	**Runout length (km)**	**Friction coefficient**	**Reference**
Bogd Fault (Mongolia)	50	5	0.2	Phillip & Ritz (1999)
Saidmarreh (Iran)	45	19	0.04	Roberts & Evans (2013)
Socompa (Chile)[a]	36	40	0.07-0.14	Wadge et al. (1995)
Nomal (Pakistan)	31	11	0.2	Hewitt (2001)
Green Lake (New Zealand)	27	9	~0.07	Hancox & Perrin (1994)
Lluta (Peru)	26	~40	~0.06	Strasser & Schlunegger (2005)
Flims (Switzerland)	12	16.5	0.12	Pollet & Schneider (2004)
Tsergo Ri (Nepal)	10	~12	~0.22	Ibetsberger (1996)
Cerrillos Negros (Peru)	>9	43	0.08	Crosta et al. (2012)
Komansu (Kyrgyzstan)	~8[b]	28	0.11	This Study
Kolka-Karmadon (Russia)[c]	0.1	20 (35[e])	0.08-0.15	Huggel et al. (2005)
Huascarán (Peru)[c, d]	0.05	14 (180[e])	0.01	Evans et al. (2009)

Table 1 – Comparison of selected massive subaerial rock avalanches from around the world. [a] Volcanic debris avalanche. [b] Total volume including entrained material (see text). [c] Rock/Ice avalanches; brackets show the total runout length including the fluidised runout phase – see text for discussion. [d] This refers to the 1970 event; a similar but smaller event also occurred in 1962. [e] Total runout with secondary debris-/hyperconcentrated flow phase.

2. Rock-ice avalanche

A rock-ice avalanche (e.g. Schneider et al., 2011) occurs when a rock avalanche falls onto and erodes large quantities of ice, incorporating it into the moving mass. The ice melts, saturating the rock mass and increasing the mobility of the avalanche. A large proportion of ice to rock (2:1 or more) is required to saturate the debris and alter the mode of motion (Sosio et al, 2012). There are several examples of extremely mobile rock-ice avalanches with which the Komansu deposit can be compared, the most notable of which are the 1970 Huascarán event in Peru (Evans et al., 2009), the 1987 Rìo Colorado event in Chile (Hauser, 2002) and the 2002 Kolka-Karmadon event in Russia (Huggel et al., 2005). In each of these events a moderately large (~10^7 m^3) collapse of rock and ice fell from glaciated mountains and travelled huge distances downstream: in the Huascarán event, debris reached the Pacific Ocean 180 km away (Evans et al., 2009). However, each event contained at least two different phases of motion: an initial (proximal) rock-ice avalanche phase followed by a distal debris- or hyperconcentrated flow. In each case the extent of the rock-ice avalanche phase is comparable to the Komansu deposit, albeit with very much smaller volumes. No evidence of a debris flow or hyperconcentrated flow was found downstream of the Komansu deposit, but given the age of the event this does not conclusively disprove the occurrence of a rock-ice avalanche.

The basal fragmented layer found in the distal exposure of the Komansu event, however, is difficult to reconcile with the water-saturated motion of a rock-ice avalanche, which would be likely to move as a fine-sediment slurry containing larger material (Fig. 10).

It is certainly likely that a significant amount of ice was included in the Komansu runout. Strom (2014) suggested that the presence of ice explained the chaotic hummocky topography; however, it is significant that the Komansu deposit bears little morphological resemblance to the three examples of rock-ice avalanche deposits discussed. Furthermore, the presence of hummocks in the Socompa volcanic debris avalanche deposit, which did not involve ice, shows that ice is not required to generate such hummocks. Rock-ice avalanche deposits resemble those of slurry flows in their distal regions (Fig. 10); photos from the Kolka-Karmadon (Huggel et al, 2005) and

Huascarán (Evans et al., 2009) deposits show that the fluid material forms flat surfaces, lobes or compression ridges rather than hummocks.

Fig. 10 Comparison of a) rock-ice avalanche deposit above person (Huggel et al., 2002) and b) Komansu rock avalanche deposit (Strom, 2014); the rock-in-slurry composition of the rock-ice avalanche is evident in contrast with the Komansu deposit exposures. Note the jigsaw-like structure of the Komansu deposit showing entrarinment of rounded fluvial material (lighter).

Both the Huascarán and Kolka-Karmamdon events involved very large quantities of ice. The initial failure of the Huascarán event involved ~6×10^6 m^3 of rock debris and ~1×10^6 m^3 of ice, with >15×10^6 m^3 of snow and ice being entrained in the flow (Evans et al., 2009), giving a total ice-to-rock ratio of ~2.7:1. During the Kolka-Karmadon event, an initial failure of >10×10^6 m^3 of rock debris and >8×10^6 m^3 of ice fell onto the Kolka glacier, eroding away between 60 and 90 $\times 10^6$ m^3 of ice from the glacier (Huggel et al., 2005) with an ice-to-rock ratio of between 7:1 and 10:1. The Komansu deposit is considerably larger than the Huascarán (0.05 km^3), Rìo Colorado (0.015 km^3), and Kolka-Karmadon (0.1 km^3) events. If the present day volume of 3-5 km^3 corresponds to the total volume of the Komansu event, *at least* 6-10 km^3 of ice would have been required to generate a rock-ice avalanche; correspondingly more would be needed to cause the inferred 5-10 km^3 event into a rock-ice avalanche. It is difficult to explain the availability of such a large volume of ice, especially given that the age of the deposit appears to correspond to a time after the region's glaciers began to retreat.

Despite a rock-ice avalanche mechanism being able to explain the extreme mobility of the Komansu deposit, the morphological and sedimentary evidence, combined with the requirement for an extremely large volume of ice, suggest this was not the mode of emplacement.

Parameter	Value
Debris volume, $\boldsymbol{V}$ (m^3)[a]	~8×10^{10}
Final deposit elevation (m)	2,800
Source zone elevation (m)	5,800
Fall height, $\boldsymbol{H}$ (m)	3,000
Runout length, $\boldsymbol{L}$ (m)	28,000
Apparent coefficient of friction	0.11
Fahrböschung ($\tan^{-1}$ H/L)	6.1°

Table 2 Runout parameters of the Komansu rock avalanche. [a] Refers to total volume including entrained material (see text).

3. Supraglacial travel

Rock avalanches that travel over glaciers are very much thinner (usually ~ 10 m), and spread much more, than those that travel over non-glaciated terrain, having a basal friction coefficient of ~0.1 (e.g. McSaveney, 1978; Eisbacher, 1979; Evans and Clague, 1988). This suggests that the Komansu event could achieve its 28 km runout with a volume of a few cubic kilometres if it was emplaced supraglacially. However, supraglacial rock avalanche deposits commonly have longitudinal ridges rather than well-defined hummocks (e.g. Sherman Glacier, Alaska (McSaveney, 1978): Mt Munday, Canada (Delaney and Evans 2014)), and these are absent from the Komansu deposit. In addition, the thickness of the Komansu deposit with up to 40-m high distal hummocks suggests that distal emplacement, at least, was not supraglacial. Finally, the inferred mid-Holocene timing of the event suggests that glaciers at that time were not greatly more extensive than at present, so that only part of the confined valley travel could have been supraglacial, and this on its own cannot explain the runout.

Thus, while all three of these emplacement mechanisms are feasible, none adequately explains the extreme mobility observed. The available morphological and sedimentary evidence favours a rock avalanche origin with a volume much greater than the present-day exposed deposits, but such a volume is not feasible. It is critical from a present-day hazards perspective to conclusively identify a runout mode; for instance, if substantial glaciers were required to explain the runout distance, then present-day conditions might imply that such long runout is not possible under modern conditions.

We attempt to resolve this conundrum by considering the mobility and morphology of volcanic debris avalanches, whose runout lengths are typically larger than those of rock avalanches of similar volumes.

<u>Comparison with Socompa volcanic debris avalanche</u>

The basal contact shown in Figs. 7 and 8 has a thin (~10 cm) layer of very fine-grained material separating the mass movement deposit from the alluvial deposits (Fig. 9). This material has a consistent fine-sand-to-clay size distribution and distinct upper and lower boundaries (Fig. 9). The overlying ~10 m thick rock avalanche unit contains large (up to boulder size), angular clasts supported in a fine (up to coarse sand size) matrix. This stratification is likely the result of high normal and shear stresses in the basal region resulting in concentrated comminution of rock debris in this area (Davies et al., 2010).

Similar stratification has been identified in the Socompa volcanic debris avalanche deposit in Chile (Le Corvec, 2005) which occurred 7,200 yr B.P., had a total volume of 36 km^3 (only ~25 km^3 was involved in the runout however, with the rest remaining proximal to the volcano), and a runout of 40 km (Wadge et al. 1995; Van Wyk de Vries et al., 2001). The Socompa deposit has a heavily fragmented lower unit containing thin internal shear bands and an overlying, less fragmented breccia deposit (Wadge et al. 1995; Le Corvec, 2005). Furthermore, the Socompa deposit also has prominent non-striated hummocky topography and an average thickness on the order of 40 m (Davies et al., 2010) and therefore bears notable similarities to the Komansu deposit.

The process of dynamic rock fragmentation proposed by Davies et al. (2010) provides a plausible mechanism for the occurrence of low basal shear resistance. This suggests that when fragmentation is concentrated in a basal layer, continuous and widespread explosive failure of rock particles exerts a pressure on the overlying material, supporting its weight and reducing the basal effective stress, and thus the apparent coefficient of friction. This mechanism is therefore able to explain the presence of a highly fragmented basal unit, an overlying less fragmented unit, and the reduced basal shear resistance noted in both the Socompa debris avalanche deposit and the Komansu deposit. Lateral and longitudinal spreading of the deposit over the weak basal layer explains the hummocky morphology. However, it is not able to explain why the Komansu friction coefficient (Table 2) corresponds to a debris volume significantly larger than that which appears to have been involved.

The Socompa event was a volcanic debris avalanche, and these generally appear to involve higher mobility than non-volcanic rock avalanches (by a factor of about 2; Legros, 2000; Ui, 1983; Siebert, 1984; Dade and Huppert, 1998), but the absence of volcanoes in the Trans Alai range appears to preclude this mechanism as an explanation of the Komansu runout. However, the reason that volcanic debris avalanches are more mobile than non-volcanic rock avalanches is not because of differences in rock properties, but rather due to the high voids ratio and water content of a volcanic edifice (e.g. Glicken, 1996) compared to the relatively void-free intact rock that forms the source of a rock avalanche (Davies & McSaveney, 2009). Despite having a high water content, volcanic debris avalanches such as Socompa have still produced a highly fragmented basal layer demonstrating that while they have sufficient water content to increase mobility they are not saturated. Glicken (1996) confirmed this; he estimated that the edifice of Mt St Helens had an initial porosity of about 14% and was about 92% saturated, while following deposition the debris avalanche had 25% porosity and 45% saturation due to a total volume increase of 0.4 km^3 by bulking of the debris. A non-volcanic rock avalanche, by contrast, will be essentially completely dry because the source rock contains very little water, and the high bulking creates large volumes of void space.

Proposed emplacement sequence

At the time the Komansu event occurred there was certainly a large amount of ice and snow present in the Trans Alai range. If it we assume the source zone was covered in 50-100 m of ice, which seems reasonable given the current levels of ice in the present-day range, then a total of 0.5 km^3 of ice may have been involved in the initial failure. We estimate that the total rock volume from the source area was 4 km^3 (Fig. 4) which likely bulked to 5 km^3 resulting in a void space of 1 km^3. Thus the 0.5 km^3 available ice would have resulted in a saturation of ~50%, which is remarkably similar to Glicken (1996)'s estimate of the Mt St Helens debris avalanche. It is therefore likely that the Komansu rock debris would have behaved in a similar manner to a volcanic debris avalanche. To explain the Socompa runout requires that Eq. (1) becomes

$$L = 14(V)^{1/3} \qquad (2)$$

On this basis a runout of 28 km requires $V = 2^3 = 8$ km^3. Thus it is possible to explain the extreme mobility of the Komansu event with a smaller volume than required by dry rock avalanche mechanisms, assuming mobility similar to that of Socompa and Mt St Helens.

However, this volume is still at least twice that of the probable source zone. Nevertheless, several historic rock avalanches have entrained a large amount of material during runout, increasing their volume and mobility substantially. Hungr and Evans (2004) reported multiple rock avalanche events of various volumes which had entrainment ratios (volume entrained/collapse volume) >1, especially those which interacted with colluvium, alluvium, and glacial deposits. The Komansu deposit is likely to have interacted with all three of these deposits during its long runout. The observed entrainment ratios are sufficient to increase the initial 4 km^3 debris volume suggested from the source zone, to the 8 km^3 volume required to explain a 28 km runout length. Furthermore, this large scale entrainment of material appears to conform with observations by Strom (2014) of abundant fluvial material within the deposit (Fig. 10). Assuming most of this entrainment happened during the first half of the runout (15 km), the debris would have filled the valley reach which has an average width of ~4 km (Fig. 2) suggesting an erosional depth of ~60 m. If entrainment occurred along the entire runout this depth would obviously be substantially less.

We therefore suggest that a likely explanation for the extreme mobility of the Komansu event is an initial failure of ~4 km^3 of dry rock debris, together with a large volume of glacial ice, which during proximal runout entrained a further ~4 km^3 of substrate plus more glacial ice, resulting in unsaturated flow processes similar to a volcanic debris avalanche with intense basal fragmentation, generating a runout length of 28 km. While this suggestion includes several assumptions, it is able to adequately explain the morphological and sedimentary evidence observed and is consistent with source volume.

Runout over Frozen Ground

A final factor which should be considered is the effects of the rock avalanche moving across frozen ground. Due to its elevation, the region is exceptionally cold for at least half the year and has likely been so for most of the Holocene. Given the large volume and the proximity to a large, active fault, a seismic initiation is most likely and thus there is a 50% chance the event occurred when the ground was frozen. Runout over frozen ground is likely to reduce basal friction and increase mobility however, it is not known how much of an influence this is likely to have. Thus it is not currently possible to say whether, and how much, this influenced runout.

Hazard

The identification of the Komansu rock avalanche presents several important issues for future hazard analysis. Firstly, the re-interpretation of this deposit as a rock avalanche deposit rather than a glacial deposit, combined with several other notable examples globally, suggests that massive landslides may be more common than previously thought, as found by Hewitt (1999) in the Karakoram Himalaya. Further assessment of other deposits within the Alai Valley is required in order to understand how frequently such events occur in this region. Continued global assessment of deposits such as the Komansu deposit are likely to yield further examples of this misinterpretation. Thus mountainous areas with glacial deposits, particularly those close to active faults, are likely to have a higher rock avalanche hazard than currently believed. Further, if sufficient ice can be incorporated, the runout of rock avalanches in glaciated mountains may be significantly longer than that in the absence of glaciers.

The mechanism(s) involved in the excessive runout length are also important. Most villages within the Alai Valley are situated at its northern extent, at the base of the Tien Shan (Fig 1). Prior to identification of the Komansu rock avalanche, the major mass movement hazard perceived to these villages was that from the Tien Shan. However, the Komansu rock avalanche suggests that these locations have always had the additional threat of long runout rock avalanches originating in the Trans Alai. Our work demonstrates that this runout was the result of rock debris and ice collapsing and entraining large volumes of material resulting in an excessive runout length. If runout over glacial ice was necessary to explain the deposit extent then the retreat of glaciers in the region would suggest that a recurrence of a similar event is unlikely as future events would have only limited runout length over ice. Similarly, glacial retreat reduces the possibility of very large amounts of ice being included in any future event, and thus the possibility of a long runout rock-ice avalanche. However, since the runout appears to be satisfactorily explained by wet rock debris entraining large volumes of material during initial runout, it is possible that a long runout rock avalanche could occur at any time. Quantification of this hazard requires knowledge of how the ice:rock ratio affects increases in runout distances, which is an important topic for future work. Given the potential for a large-magnitude earthquake in the region, the occurrence of a future large-volume wet rock avalanche with similar runout characteristics cannot yet be discounted. Understanding the mechanism involved during runout is therefore vital to better understanding these events and the hazard they pose.

Conclusions

Reanalysis of a deposit in the central Alai Valley in southern Kyrgyzstan that has previously been thought to be of glacial origin shows instead that it is a massive coseismic rock avalanche deposit. This deposit, on the true right of the Komansu River, originally covered an area ~100-150 km^2, contained a volume of about 8 km^3, and had a total runout length of ~28 km. It is thus one of the longest-runout subaerial, non-volcanic rock avalanches thus far identified on Earth. Runout of the debris was halted when it reached the lower slopes of the Tien Shan at the northern boundary of the Alai Valley. Here the debris ran uphill for up to 100 m suggesting a velocity of > 45 m s^{-1} before it began to run uphill. The event appears to have occurred about 5,000-11,000 years ago, and at least 50% of the deposit has been eroded or buried since emplacement. The most likely trigger was a large

(>M7) earthquake on the range-bounding Main Pamir Thrust; this fault has a fast slip-rate and has produced earthquakes of this size in recent history. The mechanism responsible for the long runout appears to have been a rock avalanche that was wet but not saturated, and behaved in a similar way to a volcanic debris avalanche; this allows the source area rock volume (~ 4 km^3), together with substantial ice, to fall and entrain a similar volume of substrate and further glacial ice, giving mobility similar to that of the Socompa volcanic debris avalanche. Additional mapping, field investigations, and analysis of other glacial landforms in active mountain belts worldwide may assist with the discovery of other large-runout rock avalanches and with correspondingly improved hazard assessments.

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